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19. CLIMATIC AND ENVIRONMENTAL VARIABILITY IN THE MID-LATITUDE EUROPE SECTOR DURING THE LAST INTERGLACIAL-GLACIAL CYCLE

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Introduction

Key criteria when constructing regional summaries of the sequence and patterns of climate change during the last interglacial-glacial cycle are: (i) well-dated, high resolution palaeo-environmental data-sets based on multi-disciplinary investigations; (ii) the construction of sophisticated databases able to store, and facilitate analysis of, such complex data-sets; and (iii) the development of closer links between the 'palaeo-data' and global climate modelling communities, in order to test ideas about the nature and causes of abrupt climate changes. In this review we examine the nature of the palaeo-environmental data generated by studies conducted within the Mid-Latitude Europe sector of PEP III. The review is restricted to Time Stream 2 only (Gasse and Battarbee, this volume).

The Mid-Latitude Europe sector of the PEP III transect approximates to the broad band of generally low-lying land that lay between the southern edge of the northern ice sheet and the southern limit of permafrost during the last cold stage (Fig. 1). A rich array of palaeo-environmental data has been obtained from numerous sites in this region during the past 50 years or so. The cumulative results indicate that the region endured a predominantly periglacial environment during the last cold stage, but also that a number of pronounced climatic and environmental fluctuations took place. Frost-thaw cycles varied in intensity, and for brief periods the ground thawed, and boreal forests were able to migrate quite far north. Long periods of frozen ground and loess deposition were therefore interrupted by short-lived interstadial periods, during which soils formed. By contrast, environmental variability during the last interglacial stage appears to have been much less pronounced.

The western sector of Mid-Latitude Europe lies adjacent to the North Atlantic, and it has long been assumed that sea-surface temperature variations in the North Atlantic constituted the prime driver of abrupt climate changes in Europe during the last glacial cycle (Ruddiman and McIntyre 1973; Ruddiman et al. 1977). Two key questions therefore are: (i) how did changes in ice-sheet extent, North Atlantic sea-surface temperatures (SST) and thermohaline circulation modify North European climate and hydrology? And (ii) what were the magnitudes of climate changes, and of west-east climate gradients, in Mid-Latitude Europe during successive episodes of advance and retreat of the northern ice-sheets?

Since the publication of the Greenland ice-core records from the beginning of the 1990s onward (e.g., Dansgaard et al. (1993)), ideas about the frequency, magnitude and rapidity of the climate changes that affected temperate Europe during the last glacial cycle have been radically revised. Furthermore, subsequent high-resolution records from the North Atlantic (Bond et al. 1993; 1997; Cortijo et al. 2000) show remarkable similarities to the Greenland ice-core records for the last glacial cycle, suggesting a close coupling in the behaviour of the North Atlantic and the Greenland ice sheet. This new perspective has led to a re-framing of the questions being posed about the nature of ice-land-sea interactions, the degree of climate instability experienced in Europe, and the extent to which palaeoclimatic records from Europe match those obtained from the Greenland ice cores and adjacent seas (e.g., Maslin et al. (2001)). Two important questions that have recently emerged are: (i) were *all* of the climatic and environmental variations that affected Mid-Latitude Europe during the last interglacial-glacial cycle driven by North Atlantic thermohaline changes? And (ii) how quickly did the climate of Europe respond to N. Atlantic forcing during, for example, successive Dansgaard-Oeschger and Bond cycles?

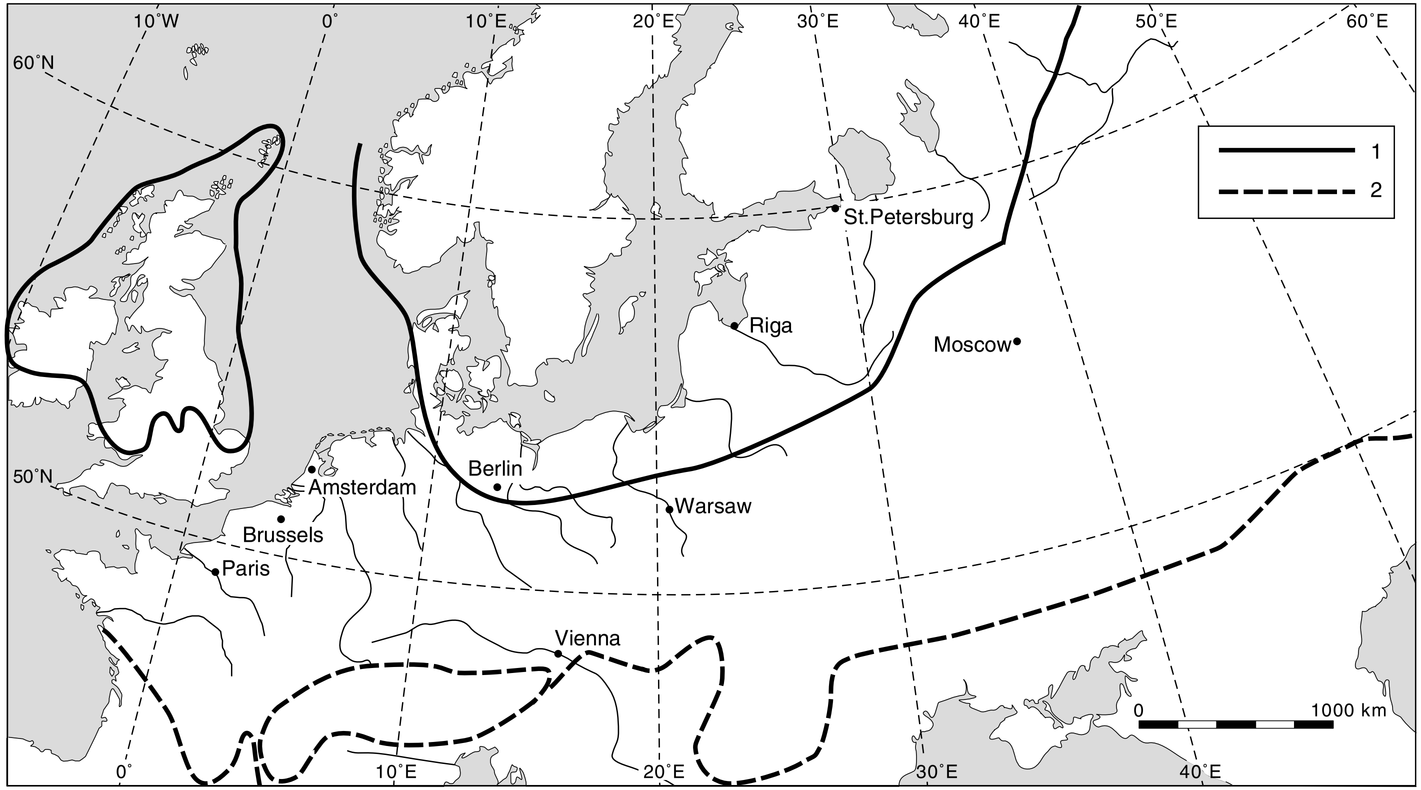

Figure 1. The Mid-Latitude Europe sector, corresponding to the area that lies between the Weichselian ice sheets of Northern Europe (full lines: 1) and the southern margin of the permafrost zone during the Weichselian LGM (broken lines: 2). Note: small central and southern European glacier extents are not represented.

Variations in climate in Mid-Latitude Europe during the last interglacial-glacial cycle

Records which span the last interglacial-glacial cycle as a continuous sequence are rare in the mid-latitude sector of Europe, due to the influences of the last (Weichselian) ice sheet and the periglacial zone which fringed its southern edge. The climate record for this long interval is therefore based on a composite model, an amalgam of the results of investigations of widely-dispersed sites that contain sediment records that span part of the cycle only, and which frequently have been dated only crudely. Exceptions may be some of the more continuous loess sequences, some of which span most of the last glacial cycle (e.g., in the Ukraine), and a few long lake sequences, such as those reported from the sites of Les Echets and La Grande Pile. These show evidence for a series of stadial-interstadial oscillations, but the chronology of the sequences is imprecise, and they do not match the Greenland ice-core records in terms of the frequency of climate oscillations inferred.

In this section of the paper we summarise the state-of-play concerning interpretations of the palaeoclimatic record obtained for 4 subdivisions of the last interglacial-glacial cycle: the last interglacial (corresponding to Marine Isotope Stage 5e - or MIS 5e), the Middle Pleniglacial (corresponding to MIS 3), the Late Pleniglacial (corresponding to MIS 2) including the Last Glacial Maximum, and the Weichselian Lateglacial (or Last Termination). This will illustrate the current problems of comparing palaeoclimatic data with, for example, the ice-core records, problems which are more severe for the earlier of these episodes than for the later ones.

Climate variations during the Eemian (MIS 5e)

The magnitude and frequency of possible climatic fluctuations during the last (Eemian) interglacial is a topic of widespread interest at present, in view of the fact that the Eemian is the most recent episode of fully interglacial conditions which was not affected by human-induced influences on climate. Hence, stratigraphical records for this period offer the best opportunity for establishing the natural sensitivity of global climate during a full interglacial period.

Some of the evidence obtained from the GRIP ice core (Greenland), which is thought to extend back to the Last Interglacial, suggests that high amplitude temperature fluctuations characterise isotope stage 5e (Dansgaard et al. 1993). However, these features do not have close parallels in the GISP2 ice core at Summit (Taylor et al. 1993), nor in a number of high-resolution isotope records obtained from North Atlantic marine cores (McManus et al. 1994). Palaeobotanical records from continental Europe serve to cloud the issue further. Field et al. (1994), for example, used a transfer function approach, interpreted palaeobotanical records from the site of Bispingen, Germany as indicating an episode of marked winter cooling, though without substantial changes in summer conditions, during the mid-Eemian. Their interpretation may be supported by records from Southern Europe (e.g., Thouveny et al. (1994)) and some marine records (e.g., Seidenkrantz et al. (1995)). On the other hand, some researchers interpret Eemian palaeobotanical records, including the Bispingen site, as indicating that the Eemian was a period of uninterrupted warm climatic conditions (e.g., Menke and Tynni (1984), Frenzel (1991), Zagwijn (1996), Litt et al. (1996), Boettger et al. (2000), Drescher-Schneider (2000)). The results obtained by

Field et al. (1994) using the transfer function approach contrast with those obtained using an indicator species method (Fig. 2). The latter suggest that the early part of the last interglacial was influenced by sub-continental conditions, while the middle part (*Carpinus* phase, zone 5) was characterised by a markedly more oceanic climatic regime, as seems to be indicated by the persistent records of *Hedera*, *Ilex* and *Buxus* in the mid-Eemian (see Frenzel (1991), Zagwijn (1996), Litt et al. (1996), Aalbersberg and Litt (1998)). The probability density function (*pdf*) method (Kühl et al. 2002; Litt et al. 2001) has been applied, involving the definition of a 'climate-space' in much the same way as has been developed for analysis of fossil beetle assemblages (Atkinson et al. 1987). It supports the interpretations based on the indicator species method, for they suggest that the most probable January and July temperatures during the Eemian were little different to those prevailing in Mid-Latitude Europe today (Fig. 3).

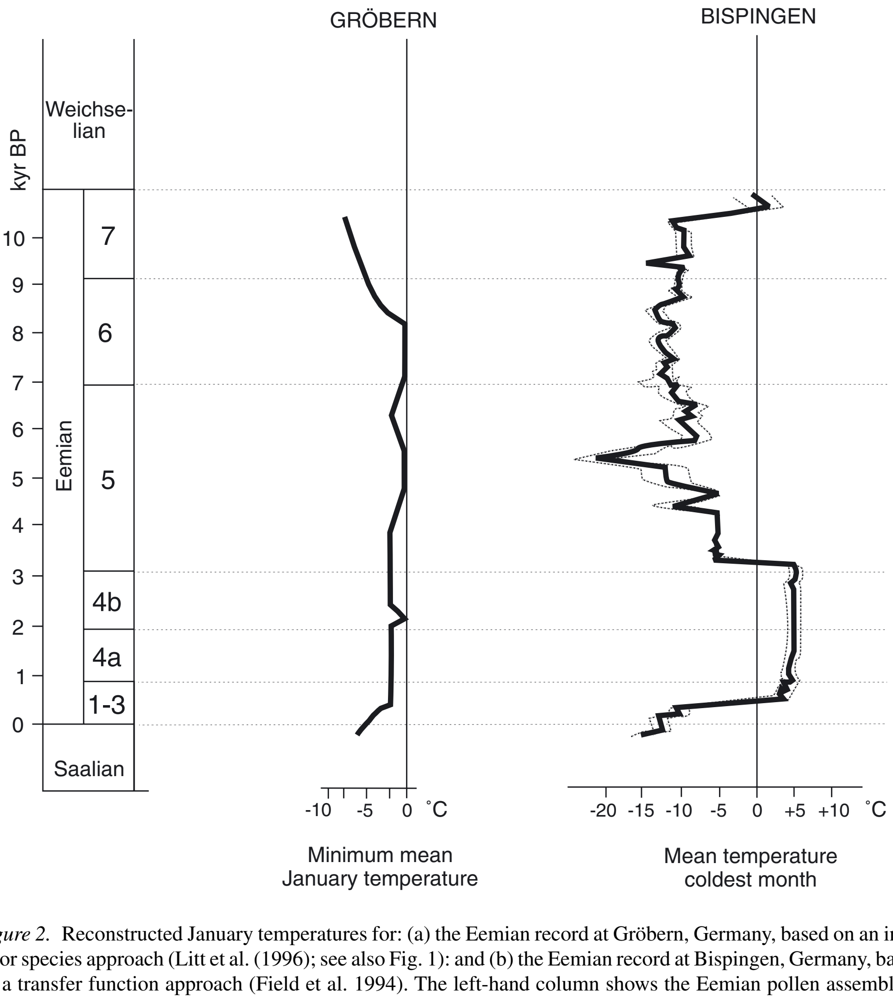

Figure 2. Reconstructed January temperatures for: (a) the Eemian record at Gröbern, Germany, based on an indicator species approach (Litt et al. (1996); see also Fig. 1): and (b) the Eemian record at Bispingen, Germany, based on a transfer function approach (Field et al. 1994). The left-hand column shows the Eemian pollen assemblage zones.

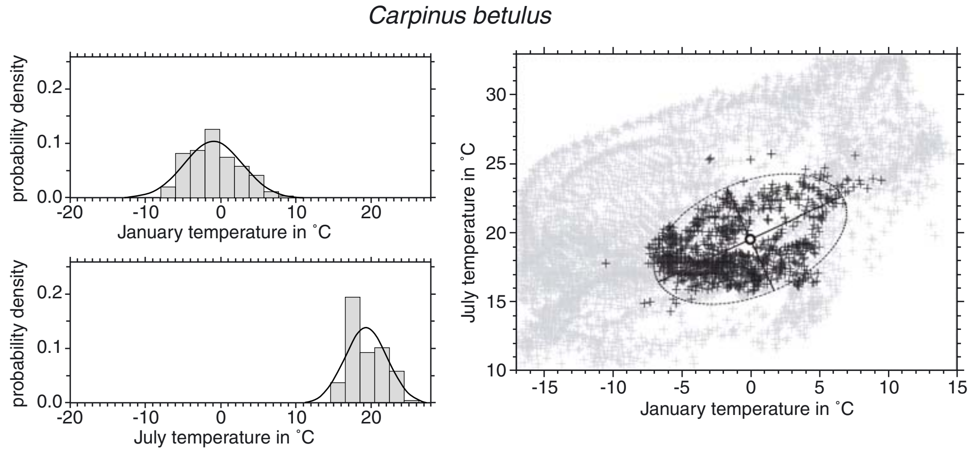

Figure 3. The probability density function (pdf) method applied to a fossil assemblage record from the Gröbern site, consisting of remains of *Acer, Carpinus betulus, Corylus avellana, Fraxinus excelsior, Hedera helix, Ilex aquifolium, Picea abies, Quercus* spp. and *Taxus baccata*. The results support the interpretation based on the indicator species method, in suggesting that the most likely mean January temperature during the Eemian *Carpinus* phase (pollen zone 5) was close to 0 °C (small circle). The thick ellipse denotes the 90% uncertainty range for the combined pdf data. The present-day mean January value is represented by a cross.

The history of climate development in Europe during the Eemian remains controversial; whether interglacial periods are prone to sudden climate fluctuations remains one of the key questions to be resolved by the palaeoclimate science community (see also Rioual et al. (2001)). Some further light may be shed on this question if the investigations could be widened to include other methods and proxy types, such as, for example, the generation of beetle Mutual Climatic Range (MCR) data which uses the mutual overlap of modern climate envelopes for several species that co-occur in a fossil assemblage (Atkinson et al. 1987; Coope et al. 1998). This was attempted for the La Grande Pile sequence, though the results were of too limited a temporal resolution (see Ponel (1995)). In addition, the transfer function approach may be used, for example, for fossil chironomid assemblages. The latter method is relatively new and enables quantitative estimates of summer palaeotemperatures. It is based on measuring the relationships between the present-day distributions of chironomid taxa and modern climate gradients (Brooks and Birks 2000).

The Weichselian Middle Pleniglacial (MIS 3)

At one time it was considered that the environment of Europe during the Middle Pleniglacial (MIS 3, ca. 60–28 kyr BP) was characterised by the occurrence of only a few interstadials (Van der Hammen et al. 1967; Behre and Lade 1986). It was subsequently argued that these so-called 'interstadials' did not represent warmer conditions (Kolstrup and Wijmstra 1977; Vandenberghe 1985), which led to the suggestion, at one time widely believed, that the whole of the Middle Pleniglacial was characterised by a rather monotonous succession of tundra vegetation, uninterrupted by significant warming events (Vandenberghe 1992). This view was, however, based almost entirely upon the results of pollen-stratigraphical studies of the sediment units dating to this period. Because there was no evidence of significant changes in arboreal pollen percentages in these records, it was concluded that this indicated that there had been no significant changes in temperature.

Studies of plant macrofossil and beetle records, however, suggest that there was a series of short-lived climatic warmings throughout MIS-3. Not all of these can be found in stratigraphical succession at a single site, and they cannot yet be precisely dated. Except for the Hengelo Interstadial, there is no correlation with the 'interstadials' previously defined on the basis of pollen stratigraphy. It is therefore difficult to establish the full effect on Europe of each of these warming events.

Certain characteristic periglacial phenomena and landforms are diagnostic of continuous and discontinuous permafrost. Many of them are often well preserved in the geological record (Huijzer and Isarin 1997), the most widespread being thermal contraction wedges, large cryoturbation structures and perennial frost mounds (in permafrost regions), and small cryoturbations and frost fissures (the latter can also occur under conditions of deep seasonal frost). If these phenomena can be dated precisely, then they provide an indication of the severity (especially in terms of mean annual air temperatures) of ground freezing conditions (e.g., Vandenberghe and Pissart (1993)). Caution is required, however, when interpreting data derived using this approach (Van Huissteden et al. 2003).

Some important advances are beginning to be made. For example, the Hengelo Interstadial (ca. 39–36 ^{14}C kyr BP), originally identified by Zagwijn (1974), has been recognised more widely in Mid-Latitude Europe and there is increasingly robust proxy data to reconstruct the climatic conditions that prevailed during that event (Van Huissteden 1990; Kasse et al. 1995). It was preceded by a distinctly colder phase, the Hasselo Stadial (ca. 40–38.7 ^{14}C kyr BP), during which permafrost developed in The Netherlands and in Germany (Van Huissteden 1990; Kasse et al. 2003). Just prior to this Hasselo Stadial, distinctly warmer conditions were recognised in Europe by Bos et al. (2001) from evidence in East Germany, an event which probably correlates with the Upton Warren Interstadial of the British Isles (Coope 1977). In both the latter event and in the Hengelo Interstadial, summer temperatures rose by ca. 2 °C to 3 °C, in marked contrast to the bitterly cold conditions that had generally prevailed in the region during the intervening stadial (Fig. 4). In fluvial sediment successions the evidence is more difficult to interpret, since the disappearance of permafrost could also be induced by river flooding (Kasse et al. 1995). Following the Hasselo Stadial, permafrost conditions appear to have persisted up until the Late Pleniglacial only on loess subsoils in Western Europe and in more eastern regions (Haesaerts 1974; Van Vliet-Lanoë 1989; Vandenberghe et al. 1998a; Vandenberghe and Nugteren 2001; Kasse et al. 2003). The loess record too points to frequent climatic oscillations on a millennial time scale (e.g., Antoine et al. (2001), Rousseau et al. (1998), Schirmer (2000), Weidenfeller and Zöller (1999)). In this respect, certain key "marker loesses", originally defined in the Czech Republic and Slovakia, promise to provide important stratigraphic links (e.g., Rousseau et al. (2001)).

One technique that offers much potential for the dating and correlation of loess sequences is the analysis of δ^{13}C variations in the organic matter contained within loess deposits. Hatté et al. (2001) have shown that δ^{13}C variations in a loess succession of last glacial age from the upper Rhine area can be correlated with the GRIP/GISP Greenland

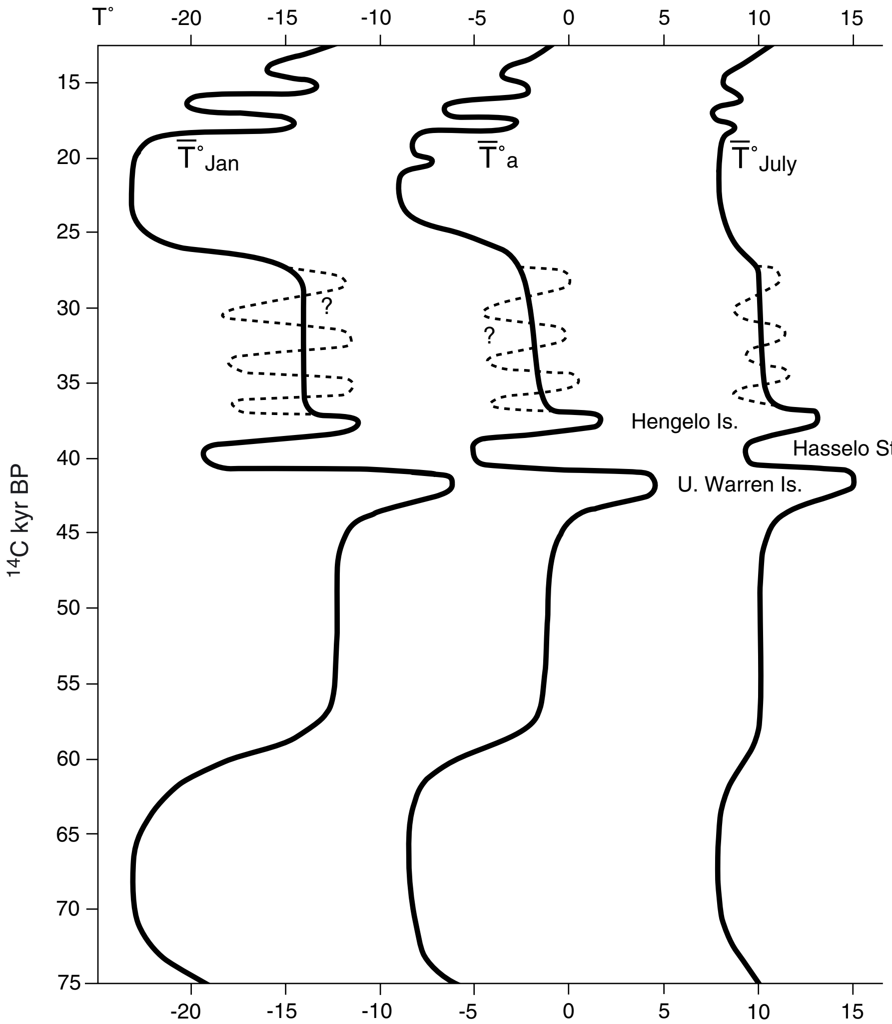

Figure 4. Variations in mean annual temperature (T°a) and in mean temperatures of the warmest (T°July) and coldest (T°Jan) months during the Weichselian Pleniglacial in Western Europe, as reconstructed using a multi-proxy palaeoclimate approach.

ice isotopic record. These results indicate that the loess of the Rhine area during the last glacial stage was not deposited in a dry steppe environment, as previously assumed, but instead under a humid forest steppe or tundra environment, while palaeo-precipitation reconstructions point to annual precipitation values similar to those of the present day, with the exceptions of drier phases towards the end of MIS 2 and MIS 4.

A state-of-the-art model of changing summer, winter and mean annual temperatures during the Weichselian Pleniglacial in Western Europe is presented in Figure 4, though much remains to be refined, in terms of quantifying the magnitude of the climate oscillations as well as establishing the precise ages of the principal climate shifts. The latter is particularly problematic because of serious discrepancies between different models used to calibrate radiocarbon dates for this period (e.g., Kitagawa and van der Plicht (1998a, 1998b), Beck et al. (2001)). The scheme in Figure 4 remains rather tentative, and comparisons with detailed ice-core and marine records for MIS 3 cannot yet be made with a reasonable precision.

The Last Glacial Maximum (MIS 2)

The LGM is a very distinct signal in records from mid-latitude Europe. Many records can be assigned to this time period, and the prevailing climatic conditions can be reconstructed in quite some detail. Accordingly, relatively robust palaeoclimatic data can be provided to palaeoclimatic modellers for global reconstructions that focus on the LGM (Velichko 1984; Van Vliet-Lanoë 1989; Vandenberghe and Pissart 1993; Huijzer and Vandenberghe 1998).

Indications for continuous permafrost are very widespread in Mid-Latitude Europe during the coldest phase of the LGM. There are, however, also some indications that ice wedges degraded temporarily, but resumed their activity shortly afterwards (Van Vliet-Lanoë 1992; Van Huissteden et al. 2000). It is not certain that such (partial) permafrost degradation had a climatic origin, but the possibility is not discounted. Continuous permafrost disappeared finally around 19–20 cal kyr BP in the coversand region (Bateman and Van Huissteden 1999). Within the loess substratum in Belgium, and in the Southern Netherlands, ice-wedge formation appears to have ceased at about the same time, but then resumed shortly afterwards, with final degradation not taking place until just before 17 cal kyr BP (Fig. 5; Van den haute et al. (1998), Renssen and Vandenberghe (2003)). The dating of the coldest phase of the LGM in Mid-Latitude Europe to between 19 and 23 cal kyr BP (continuous permafrost, MAAT $<-8\,°C$) coincides roughly with the age of the lowest ocean level at the LGM (EPILOG: Mix et al. (2001)). The Scandinavian ice sheet, however, reached its maximum position in the NW Russian plain slightly later, i.e., around 18 cal kyr BP (Lunkka et al. 2001; Saarnisto and Lunkka, this volume).

A synthesis of the available coleopteran and palaeobotanical evidence for the LGM in NW Europe suggests that the mean temperature of the warmest month was approximately 8 °C. However, in the north the mean temperature of the warmest month was probably no more than 4 °C, so that a north to south gradient is evident in the data.

The $-4\,°C$ isotherm of the mean annual air temperature (representing the boundary between continuous and discontinuous permafrost, and based on such evidence as ice-wedge casts) was situated near the French-Belgian border during the LGM, and a north-south temperature gradient is implied. Nevertheless, isolated parts of Central and Northern France may have developed a more continuous permafrost because of increased altitude or because the local substrates consisted of fine-grained soils (cf. Van Vliet-Lanoë (1989)). These overall conclusions are supported by independent fossil coleopteran data.

The mean temperature of the coldest month during the LGM is based on the evidence of ice-wedge casts which indicate values below $-20\,°C$. Coleopteran evidence points to a mean temperature of the coldest month between about –25 °C and $-18\,°C$. A combination of both kinds of proxy data suggests a mean temperature of the coldest month

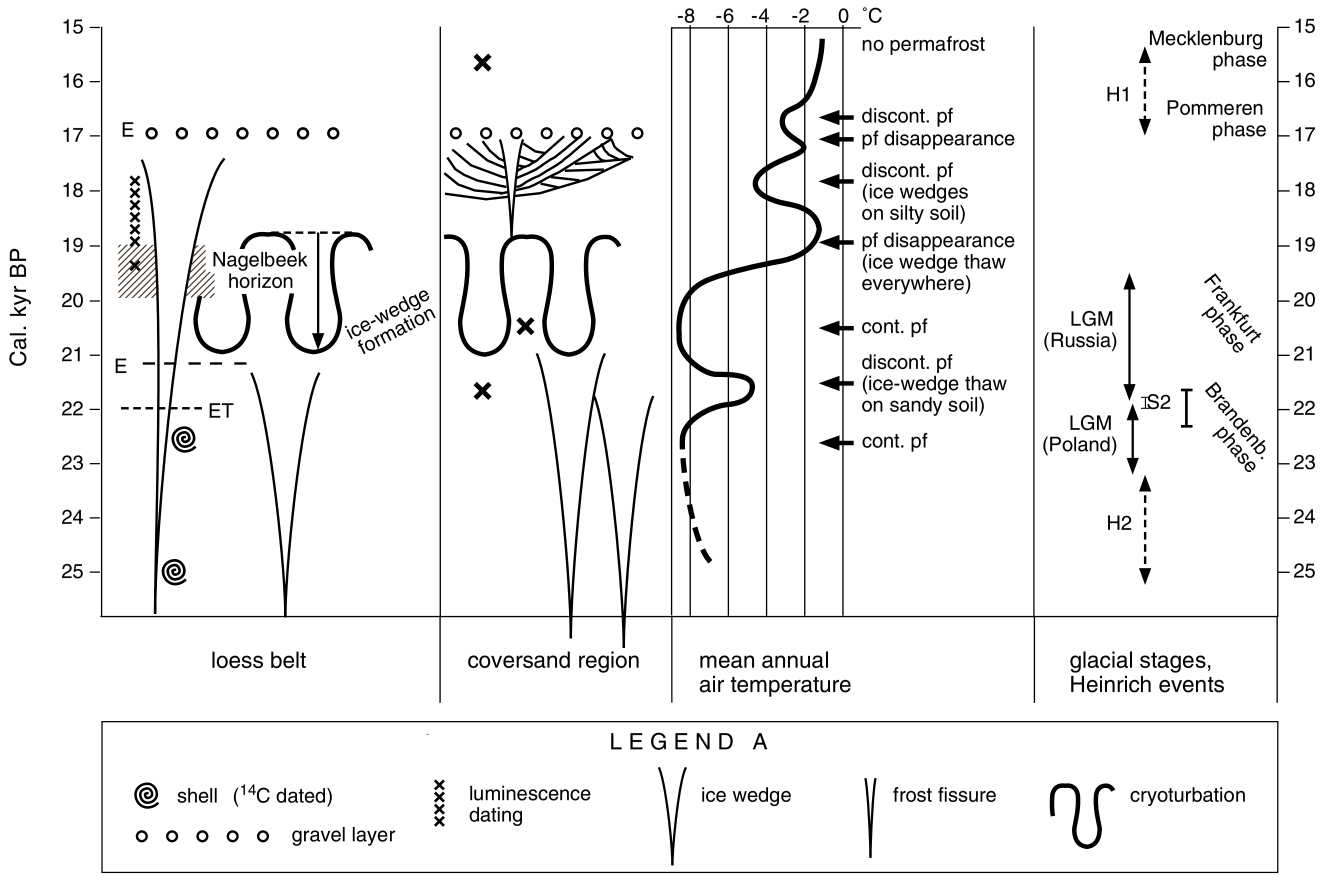

Figure 5. Summary of developments in the Dutch-Belgian region during the Weichselian Late Pleniglacial. Represented schematically are evidence for permafrost development, mean annual temperature variations, and principle episodes of glacial advance and timing of some Heinrich Events (H_1, H_2). ET = Eltville Tuff (volcanic ash layer from the Eiffel Mountains). E = erosion levels, and 'IS' = isotope stage. LGM = Last Glacial maximum (after Renssen and Vandenberghe (2003)).

somewhere between –25 °C and −20 °C. The temperature of the coldest month may also be approximated from inferences of the minimum mean temperature of the warmest month and the maximum mean annual temperature, which give similar results. As a consequence, the annual temperature amplitude during the LGM was probably of the order of 28 °C to 33 °C, indicating a high degree of continentality at that time.

From this climate overview it seems likely that the north to south thermal gradient over North-Western Europe during the LGM was much stronger than that of the present-day. This is reflected especially in the reconstructions of mean annual and winter temperatures, but is less pronounced in reconstructions of mean summer temperature.

There is ample evidence for widespread aeolian activity in the European lowlands during the LGM. Extensive accumulation of loess and sand suggests predominantly arid conditions, although there was sufficient water available for reworking of the aeolian deposits. In addition, the contrast between an extensive sand belt in the north (in Denmark, The Netherlands, Belgium, Northern Germany) and the finer loess deposits in the south (Southern Belgium, Southern part of The Netherlands, Northern France) suggests a dominant wind direction from the northern quadrant, leading to along-track sorting of particle size. However, there is evidence to suggest that wind patterns may have been more complex than this during the LGM (Vandenberghe et al. 1999).

An important phase of fluvial incision took place at the transition from the Middle to the Late Pleniglacial substages (i.e., at the start of the LGM), as recorded in many catchments in Western and Central Europe (references in Mol (1997)). At some locations the subsequent aggradation led to a change from anastomosing to braided-river systems. In general, these river pattern changes around 27 kyr are linked to increased peak discharges and a relatively high supply of sediments into the river valleys. From the collective geomorphological and sedimentary evidence, relatively high precipitation is inferred for the beginning of this time interval. The high peak discharges probably reflect the spring thawing of snow that accumulated during winter. Following this early phase, aeolian activity increased in importance, suggesting that drier conditions prevailed towards the end of the Late Pleniglacial.

The Weichselian Lateglacial (Last Termination)

A fuller understanding of the mode of operation of abrupt climatic changes requires analysis of the *spatial variations* in the palaeo-data. The availability of a large number of detailed and diverse palaeo-environmental records also offers the opportunity to apply quality screening measures to individual records (see e.g., Huijzer and Isarin (1997)). NW Europe probably has the highest density of sites with published records spanning the Last Termination/ Weichselian Lateglacial of any comparable region in the world. Over 400 palynological studies of part or all of the Late-glacial have been undertaken in The Netherlands alone (Hoek 1997). In theory, therefore, fairly sophisticated palaeoclimatic reconstructions ought to be possible, based on this archive of information. Indeed, attempts have been made to synthesise the collective proxy data, and to compare the results with model simulations (see below). There is a huge potential to generate valuable palaeoclimatic syntheses, and some tentative steps in this direction have already been made. There are, however, three significant constraints that affect the available data-base, which limit its potential to meet PEP III objectives.

Data quality

Not all of the records have been studied at a high temporal resolution, and many are based on a single proxy, or on a limited selection of proxy types. It is only in the last decade or so that truly multi-disciplinary investigations, involving large scientific teams, have become common-place (Huijzer and Isarin 1997; Vandenberghe et al. 1998b). Multi-proxy investigations of sequences that span the Last Termination and early Holocene are in progress at a number of key sites located across the Mid-Latitude Europe transect, though there is no comprehensive 'register' of these activities, and there appears to be a relative paucity of such studies in the extreme parts of the transect (Ireland and Eastern Europe).

This trend towards the organisation of large collaborative projects, designed to generate palaeo-environmental records based on multi-proxy investigations, reflects the growing awareness within the palaeo-data community that not all proxy indicators reflect climate influences directly, while some may show time-lagged responses to climate signals (e.g., Lotter et al. (2000)). The diversity of proxy indicators utilised in site investigations also appears to be growing, with some recent studies combining analyses of fossil assemblages (usually several of the following: pollen, plant macrofossil, cladoceran, chironomid, coleopteran, diatom and molluscan assemblages) with stable isotope analyses of both the sediment matrix and of selected fossil types (e.g., Lotter et al. (1997), Ammann et al. (2000), Von Grafenstein et al. (2000), Mayle et al. (1999)). This diversity of palaeo-environmental records is to be welcomed, as it may provide information on different climatic controls affecting the records, as well as independent checks on interpretations based upon different proxies.

Quantification of climatic reconstructions

Until recently, very few of the published palaeoclimatic reconstructions expressed the magnitude of inferred climate change in quantified terms. Exceptions were the palaeotemperature curves based on analysis of fossil coleopteran data (e.g., Coope and Lemdahl (1995), Coope et al. (1998)) and the climate indicator species approach applied to palaeobotanical data (Aalbersberg and Litt 1998; Isarin and Bohncke 1999), though the latter were not, until very recently, based on investigations of high temporal resolution. More recently, techniques have been developed that enable quantified inferences of mean summer temperatures to be obtained from pollen and cladoceran stratigraphy (see above and Lotter et al. (2000)) as well as fossil chironomid assemblages (Brooks and Birks 2000) using modern calibration sets. These methods hold out great promise for reconstructing the sequence and pattern of climate changes at a higher temporal resolution than hitherto. The number of sites from which such detailed records have been obtained remains relatively low, however, and their geographical spread is patchy.

Geochronological precision

One of the most serious obstacles to the successful synthesis of palaeoclimatic data for the Last Termination is the level of uncertainty in the dating and correlation methods employed. The INTIMATE[1] Group has recently reviewed the limitations affecting age estimates based

[1] **INTIMATE** (INTegration of Ice-core, MArine and TErrestrial records of the Last Termination) is a core programme of the International Quaternary Union (INQUA) Palaeoclimate Commission (INTIMATE @ http://www.geog.uu.nl/fg/palaeoclimate/intimate).

on radiocarbon dating, ice-layer counting, varve chronology (Lowe et al. 2001). The overriding problem is essentially one of temporal resolution: climate transitions, according to the Greenland ice core records, could be affected within just a few decades, while some of the climate events (e.g., the short oscillations of Greenland Interstadial 1, or the 'Bølling - Allerød phase) lasted only some 100 to 300 ice-core years. However, age estimates for events within the Last Termination obtained using ice-layer counting, radiocarbon dating and varve chronology are frequently in excess of 200 years at 1 σ (Blockley et al. pers. comm.). Clearly, it is difficult to date and correlate the various high-resolution records with the required degree of precision, and records can only be considered 'synchronous' within the rather wide uncertainty limits of the dating methods employed.

Despite these problems, some palaeoclimatic reconstructions which span the Last Termination obtained from sites in Mid-Latitude Europe show strong resemblances to the pattern of climate variations reflected in the Greenland ice-core records. Examples are inferred temperature records based on fossil beetle assemblages (Lowe et al. 1999) and on fossil chironomid assemblages (Brooks and Birks 2000) from sites in the UK, and stable oxygen isotope variations from sequences in Germany (Von Grafenstein et al. 1999), Switzerland (Schwander et al. 2000) and The Netherlands (Hoek and Bohncke 2001). There are, however, differences in detail between these records, and they are all subject to significant dating uncertainties. In none of the reconstructions are the statistical uncertainties in the chronologies represented.

There is some diversity of opinion as to whether the climate events represented in high-resolution sequences in Europe were synchronous with those represented in the Greenland ice-core and in marine records. Lowe et al. (1995) suggested a time-lag of ca. 200 to 300 years between the timing of events in the UK and of equivalent events in the GISP record. Others have suggested that climate events are synchronous between the two regions. The problem is that it is not possible to test these claims satisfactorily at present, given the inadequacies of the dating methods currently employed.

A further possible complication that needs to be borne in mind is that climate changes during the Last Termination may have been diachronous even within the confines of Europe, for there is evidence to suggest that there was a significant delay in warming at the start of the Last Termination in the north, particularly in Southern Scandinavia, by comparison with farther south (Coope and Lemdahl 1995; Witte et al. 1998). This may reflect the influence of the Scandinavian ice sheet, which may have cooled the areas in its immediate periphery. Some reconstructions therefore suggest that considerable thermal gradients prevailed across Europe at certain times during the Last Termination, much steeper than those that prevail there at the present time. Coope et al. (1998) have produced palaeoclimate maps for 8 time-slices within the Last Termination-early Holocene time-span, based on quantified palaeotemperature records from 77 sites (cf. Plate 8). These may give a useful insight into the complex evolution of the climate of Europe at the close of the last cold stage. It is the most detailed reconstruction yet attempted for Europe, which is based entirely on quantified palaeoclimate estimates.

Renssen and Isarin (1998) have employed an even more extensive palaeoclimatic data-base based on 300 site records for the 'Younger Dryas' (GS-1) period to construct palaeoclimate maps for NW Europe. The records are heterogeneous, in that a variety of proxy methods have been used to generate the palaeoclimate inferences, but an attempt has been made to derive quantified climate estimates for each record. From these data they

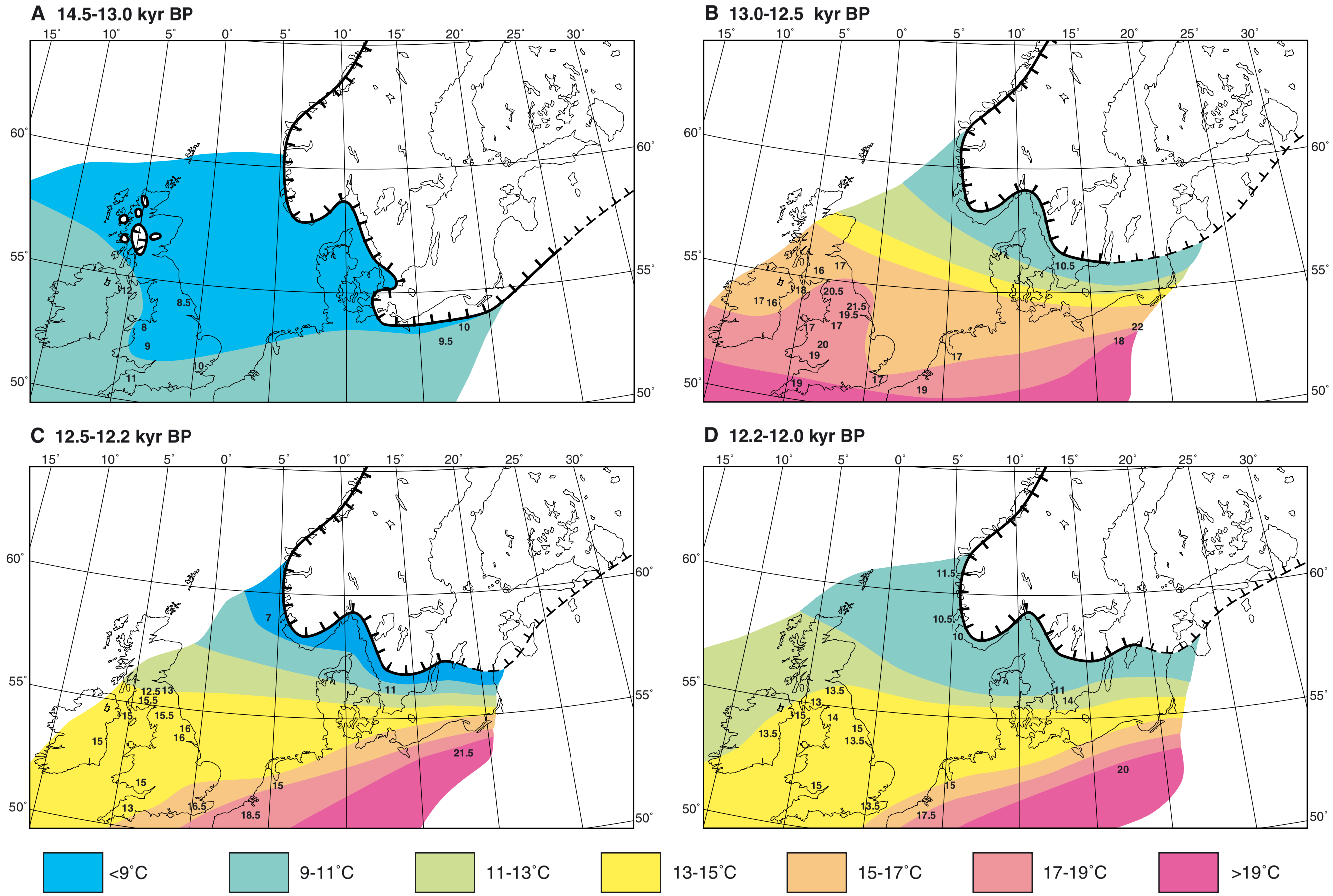

Plate 8. Generalised isotherms for the late-glacial period in Europe, based on beetle MCR interpretations. The diagram shows four of the eight time-slices for which such reconstructions were provided in Coope et al. 1998. Colour version of this Plate can be found in Appendix, p.635

have generated maps of mean winter, summer and annual temperature, with interpolated isotherms summarising climate gradients across the region during the 'Younger Dryas' (Fig. 6).

New developments and potentials

Climate modelling

Comparisons of the results of AGCM (Atmospheric General Circulation Model) simulation experiments with reconstructions of synoptic palaeoclimatic patterns in mid-latitude Europe based on proxy palaeo-data include those attempted for MIS 3 and the Younger Dryas (Isarin et al. 1997; Renssen and Isarin 1998; Isarin and Renssen 1999; Van Huissteden et al. 2003). The most important boundary conditions during those episodes, according to these experiments, were ocean surface conditions (sea-surface temperature and extent of sea ice-cover), the extent and elevation of the major ice sheets, insolation and atmospheric concentration of CO_2. Reconstructions of Younger Dryas winter temperatures are consistent with simulated (AGCM) winter conditions in North Europe but deviate from them in Southern Europe, where the simulated temperatures are 10 °C warmer than those suggested by the palaeo-data. If the palaeo-data are reliable, then they suggest that the N. Atlantic was significantly colder during the YD than is prescribed for the AGCM (Renssen and Isarin 2001). Similar results emerged from an experiment concerned with conditions during MIS 3. In both cases, sensitivity experiments focused especially on the relative contribution of sea-surface temperature, the extent of sea ice and the influence of permafrost and vegetation. Both studies strongly suggest that it is especially the winter sea-ice boundary in the northern Atlantic Ocean that controls the development and extent of permafrost conditions on the continent. Setting the sea-ice boundary too far north in the AGCM might be the reason for the discrepancy between the model outputs and the reconstructions based on palaeo-data.

Tephrochronology

Davies et al. (2002) have reviewed the potential of applying tephrochronology to the dating of Weichselian Late-glacial sequences in Europe. Altogether some 33 different tephras have been reported from sediment sequences in Europe and the NE Atlantic region which date to the period between 18.5 and 8.0 ^{14}C yr BP, though some of these are in micro-tephra form only (invisible to the naked eye). Because tephra layers are deposited virtually instantaneously (in geological terms), they effectively represent time-parallel marker horizons within stratigraphical sequences (Turney and Lowe 2001). In theory, therefore, all 33 tephras could prove valuable for correlation purposes, either in a local context or, in those cases where the ash deposits have been widely dispersed, between regional type-sequences. Davies et al. (2002) illustrate how the wider use of tephrochronology could provide a more robust geochronological framework for the dating of European sequences and of palaeoclimatic events.

It appears that there is also much potential for the application of tephrochronology to the dating and correlation of earlier events, as Wastegård and Rasmussen (2001) have

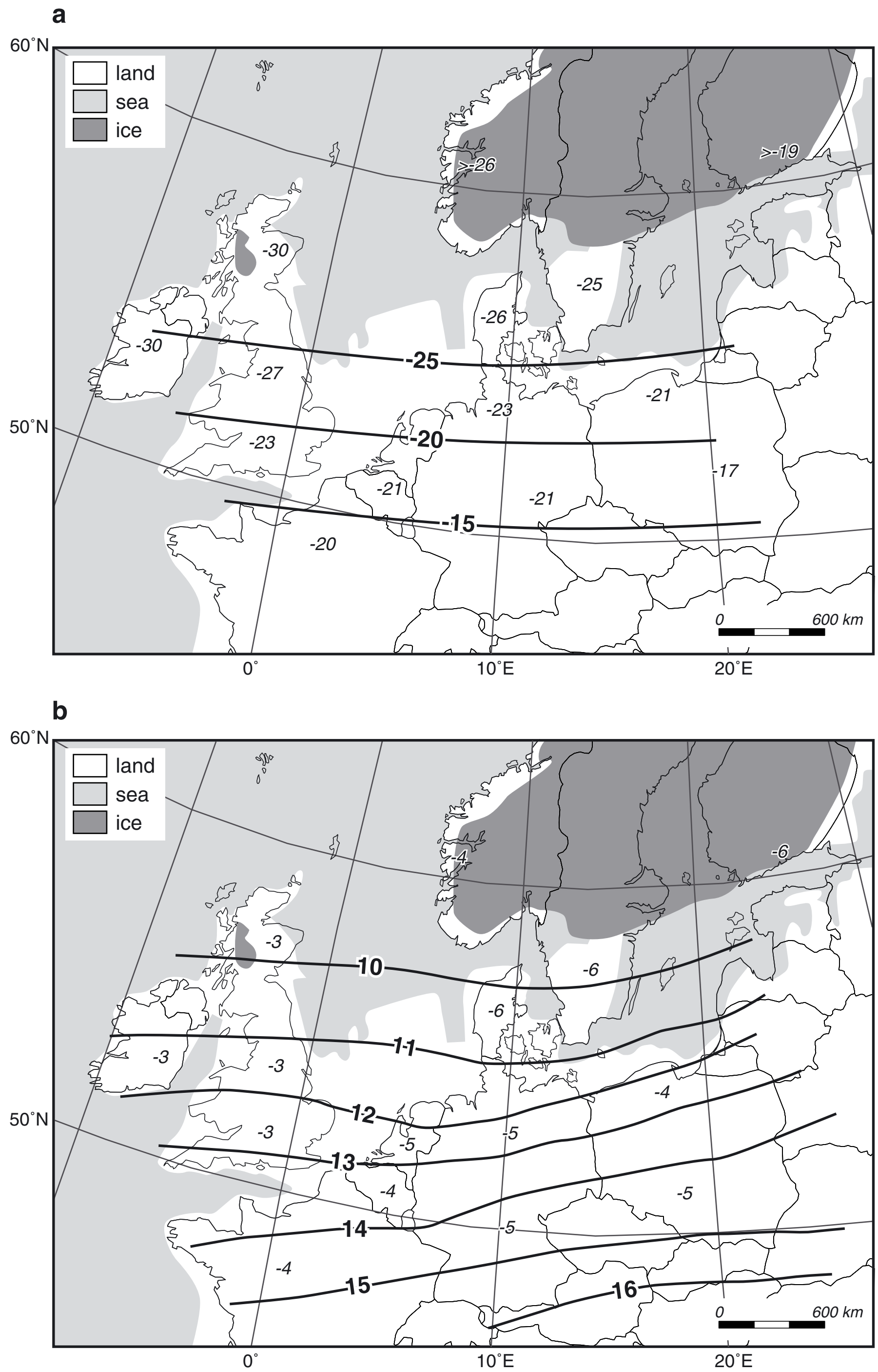

Figure 6. Reconstructed temperatures for sea-level in NW Europe for the Younger Dryas period: (a) winter (maximum mean, coldest month); and (b) summer (min, mean, warmest month) isotherms (°C) in bold and deviations from present values (°C) in italics (after Isarin et al. (1998)).

discovered tephra horizons of Icelandic province and of MIS-5 age from two cores recovered from the North Atlantic. They suggest that at least one of the tephras is likely to be widespread, and that the potential exists for its wider detection in terrestrial sequences on mainland Europe as well as in Greenland ice core records.

Annually-laminated sediments

Annually-laminated lacustrine sediments offer great potential for the detailed chronology and correlation of late Quaternary sequences, and hence for models of migration of biota, time-transgressive climate changes and other palaeo-environmental reconstructions. Varved sediments that are continuous over long intervals are comparatively rare in Europe. During the last few years, however, the Central Europe working group of the *European Lake Drilling Project* (ELDP), an international collaborative initiative funded by the European Science Foundation, has located a number of varved sediment sequences that span the Weichselian Late-glacial and has synchronised these records (Litt et al. 2001). The sites synchronised by ELDP members occur on a west-east transect from western (Eifel Maar region: Brauer et al. (1999, 2001), Litt and Stebich (1999)) and Northern Germany (Hämelsee: Merkt and Müller (1999)) to central (Lake Gościąż: Ralska-Jasiewiczowa et al. (1998)) and Eastern Poland (Lake Perespilno: Goslar et al. (1999)). Correlation of the records is based on a combination of varve counting, pollen stratigraphy, tephrochronology and stable isotope stratigraphy.

The results suggest the Younger Dryas/Preboreal transition to be quasi-synchronous in the region, and to be dated to 11,530–11,590 varve years BP. The Younger Dryas Stadial (YD) is estimated to have lasted about 1100 varve years (lakes Gościąż and Perespilno, Meerfelder Maar). The age of the Laacher See Tephra (LST), an important time marker in these sequences, has been determined to about 12,900 yr BP (varve counting at Meerfelder Maar and Ar/Ar dating), which is nearly 200 years older than the age estimated for the Allerød/YD transition (Hämelsee, Meerfelder Maar). The duration of the Allerød biozone, as defined in Jutland and in Northern Germany, was about 625–670 varve years (Hämelsee, Meerfelder Maar), whereas the older Lateglacial biozones can only be clearly defined by varve chronology in the Meerfelder Maar profile.

Regional chronologies based on annually-laminated sediments, such as those now available from Germany and Poland, are vital for providing independently-dated palaeoclimatic reconstructions that can be compared with marine and ice-core reconstructions. Precise correlations between terrestrial, marine and ice-core reconstructions are difficult to make at present, because of uncertainties with radiocarbon data-sets and with radiocarbon calibration procedures (Lowe et al. 2001). Robust age models based upon annually-laminated sediments enable the ages of climatic events in mid-latitude Europe to be dated independently from, for example, events dated using the Greenland ice-core chronologies. Hence the idea that climatic signals in mid-latitude Europe were synchronous with climatic changes in Greenland can be tested, rather than assumed, the latter having been the general practice hitherto.

It is only by adopting such an approach that regional responses to global or North Atlantic climate signals can be established objectively.

Luminescence dating

There has been striking progress in the luminescence dating of aeolian and fluvio-aeolian sands and of loess, which have accumulated in Northwest Europe during the last ten thousand years (Fig. 5; Frechen et al. (2001), Bateman and van Huissteden (1999)). These results hold out much promise for improved dating of sedimentary sequences spanning the last glacial cycle, and thereby the climatic events that can be inferred from them.

Challenges for future work

While enormous strides forward have been taken during the past two decades in the construction of more robust models of the climate history of Mid-Latitude Europe during the last inter-glacial-glacial cycle, much remains to be done.

As intimated in earlier sections of this paper, the impact of the N-Atlantic Ocean on European climate is not yet fully understood. There is a need for much more detailed comparisons between terrestrial and ocean records, which should be based on quantified palaeoclimate reconstructions, and which will need to be dated much more precisely than has been the case hitherto.

The wider use of tephrochronology, varve counting and improved approaches to luminescence dating will undoubtedly improve geochronological precision, though new approaches to radiocarbon dating are also required if the precision of age estimates for the younger events (e.g., the Weichselian Late-glacial) is to be significantly improved (cf. Lowe and Walker (2000)). The INTIMATE group has recommended a protocol for improved precision in the dating of events that fall within the Last Termination (Lowe et al. 2001).

There is a need to develop methods that will provide reconstructions of past precipitation levels. There are several methods that can be used to generate palaeotemperature variations and former wind patterns and strength, but former precipitation patterns are notoriously difficult to reconstruct since moisture is rarely the limiting factor for vegetation development and modern analogues tend to span a wide range of precipitation estimates.

There is a need to rationalise data-base facilities in Europe, to establish coherent links between them, and to expand the facilities to cope with more comprehensive data-sets. Some preliminary data-bases have been developed, but they do not cover the entire area of mid-latitude Europe (e.g., the EU-funded EPECC project at Amsterdam), or they do not have a multi-proxy remit (e.g., the European Pollen Data-base, based in Arles), or they serve as repositories of site records from many different contexts and periods (e.g., PANGAEA, based in Germany).

In view of the potential for increased clarity in how the global climate system works, a number of national initiatives have been launched to stimulate greater interaction between the palaeo-data and climate modelling communities, such as NOClim (Norway) and the UK's Rapid Climate Change thematic programme (NERC).

Summary

This paper summarises what is currently known about abrupt palaeoclimatic events and prevailing patterns of climate in the mid-latitude sector of Europe during the last interglacial-glacial cycle. It also addresses the question of whether the data that are available are adequate

to meet the scientific goals of PEP III. Significant climatic and environmental changes in this sector are reflected in (i) marked shifts in the position of vegetation belts and the distribution of fauna, some areas having experienced extreme shifts between temperate and boreal forests, and polar deserts, (ii) alternations between episodes of loess deposition and of soil formation, (iii) major modifications of river patterns and of fluvial processes, and (iv) the periodic development of permafrost. From a methodological point of view, considerable steps forward have been made in the quantification of inferred past palaeo-environmental conditions. The paper illustrates how records from key sites offer the best potential for reconstructing the sequence of abrupt climatic changes during the last interglacial-glacial cycle, but also why spatial reconstructions are required for a fuller understanding of the modes and regional effects of climatic events. The use of an array of palaeoclimatic proxy data obtained from high-resolution records from key sites, combined with assessments of the regional climatic patterns that prevailed over Europe during selected time windows, seems the best way forward for developing robust palaeoclimatic reconstructions that will be of use to the climate modelling community. We illustrate this by reference to the evidence available for the following periods: the Eemian, the Weichselian Middle Pleniglacial, the Last Glacial Maximum and the Weichselian Lateglacial.

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